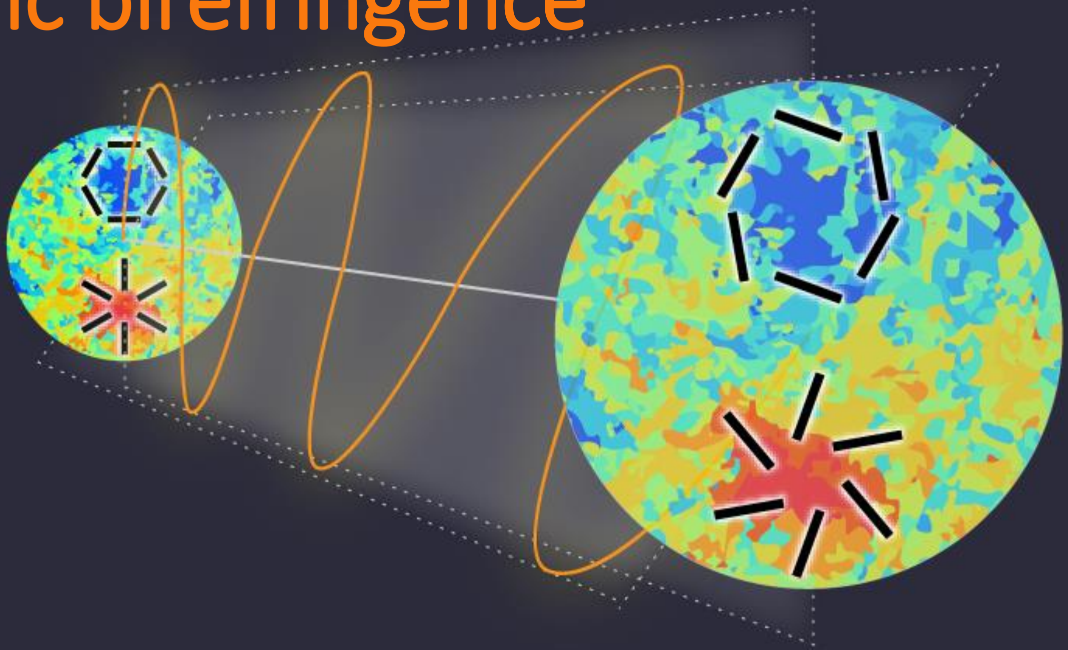
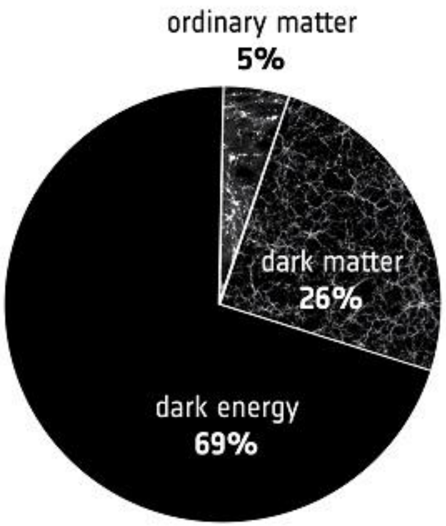
New measurements of the cosmic birefringence



Based on
- *YM & Komatsu, PRL, 125, 221301 (2020)*
- *Diego-Palazuelos, Eskilt, YM, et al., PRL, 128, 091302 (2022)*
- *Eskilt & Komatsu, arXiv:2205.13962*

Yuto Minami (KEK->RCNP, Osaka Univ.)

Introduction



Credit: ESA

- The Universe's energy budget is dominated by two dark components:
  - Dark Energy
  - Dark Matter

- Parity violation may hold the key to understanding their nature. For example, are they axion-like fields (Marsh 2016; Ferreira 2020)?

- We know that the weak interaction violates parity (Lee & Yang 1956; Wu et al. 1957)

Why should the laws of physics governing the Universe conserve parity?

Cosmic Birefringence

Carroll, Field & Jackiw (1990); Harari & Sikivie (1992); Carroll (1998)

The Universe filled with a "birefringent material"

- If the Universe is filled with a pseudo-scalar field, ϕ,(e.g., an axion field) coupled to the electromagnetic tensor via a Chern-Simons coupling:

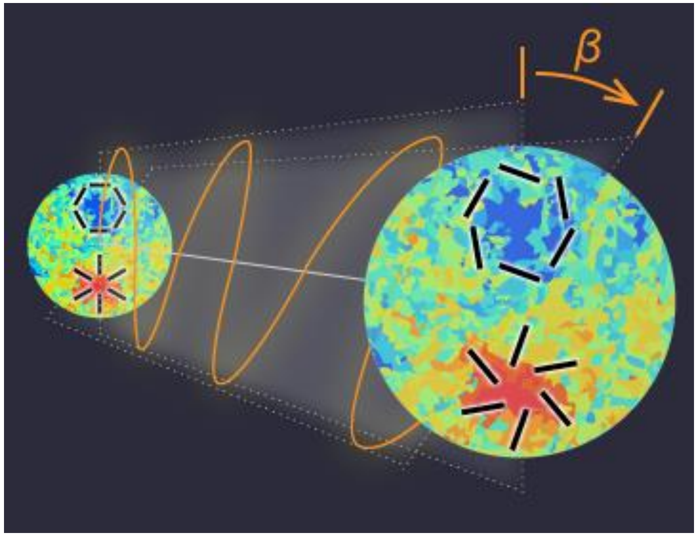
$\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}$

Chern-Simons term

$$\mathcal{L} \supset -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g_{\phi\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \quad \cdots(1)$$

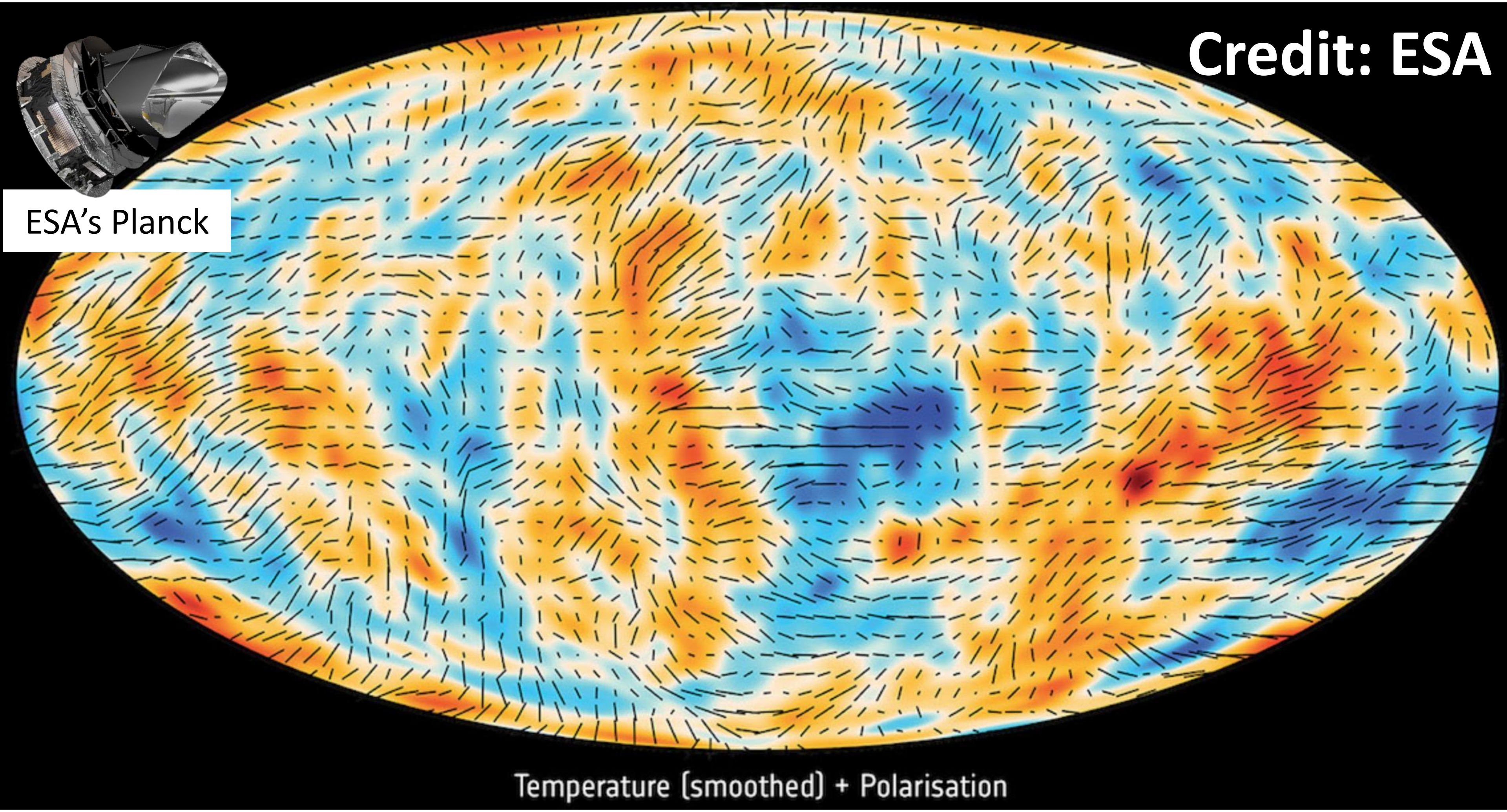
Turner & Widrow (1988)

$$\beta = \frac{g_{\phi\gamma}}{2}\int_{emission}^{observer} dt\,\dot{\phi} = \frac{g_{\phi\gamma}}{2}(\phi_{observer} - \phi_{emission}) \quad \cdots(2)$$



Difference of the field values rotates the linear polarization!

Cosmic Microwave Background as a polarised source



Emitted 13.8 billions years ago at the last scattering surface (LSS)

We know the initial $\beta = 0$

In the case of axion like particles (ALPs)

Fujita, Minami, Murai, & Nakatsuka (2020)

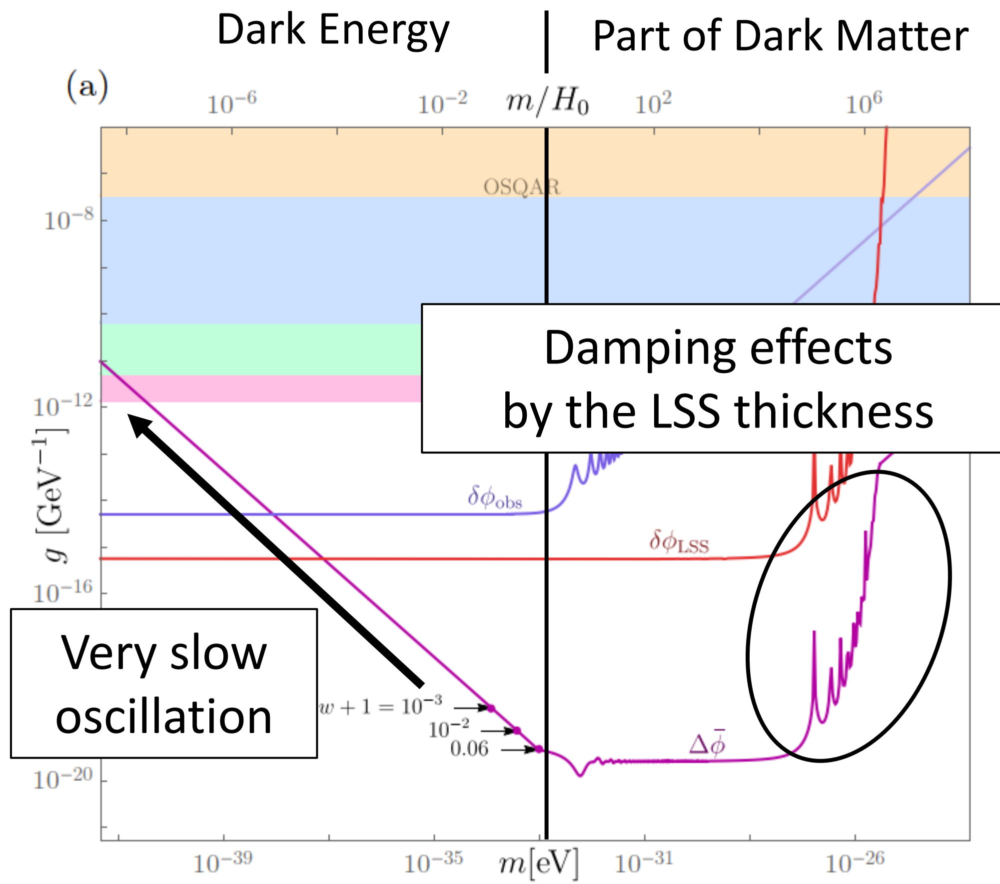
- Which is possible when we search with cosmic microwave background (CMB):

Dark Energy ?

Or

Dark Matter ?

$$\beta = \frac{g_{\phi\gamma}}{2}\underline{(\phi_{observer} - \phi_{LSS})}$$
$$= \Delta\bar{\phi}$$

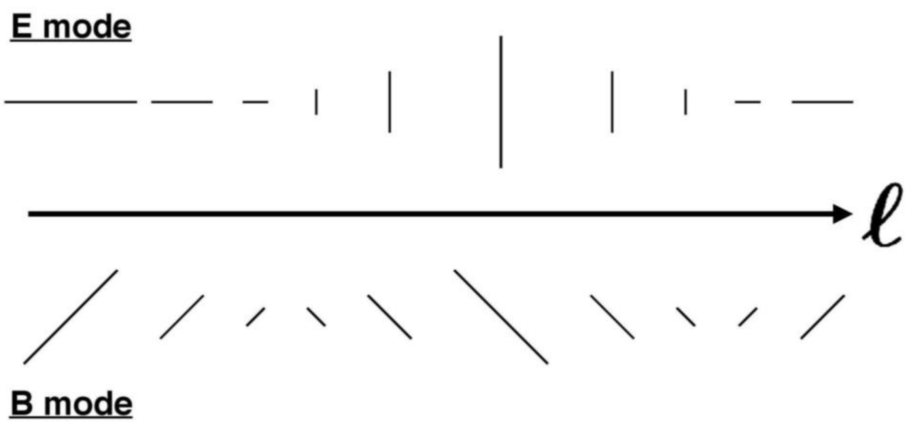


- See Marsh (2016) and Ferreira (2020) for reviews of ALPs

E- and B-mode: decomposition of linear polarisation

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)

$$E(\ell) \pm iB(\ell) = e^{\mp 2i\phi_\ell} \int d\hat{\boldsymbol{n}}\, [Q(\hat{\boldsymbol{n}}) + iU(\hat{\boldsymbol{n}})] e^{-i\ell\cdot\hat{\boldsymbol{n}}}$$



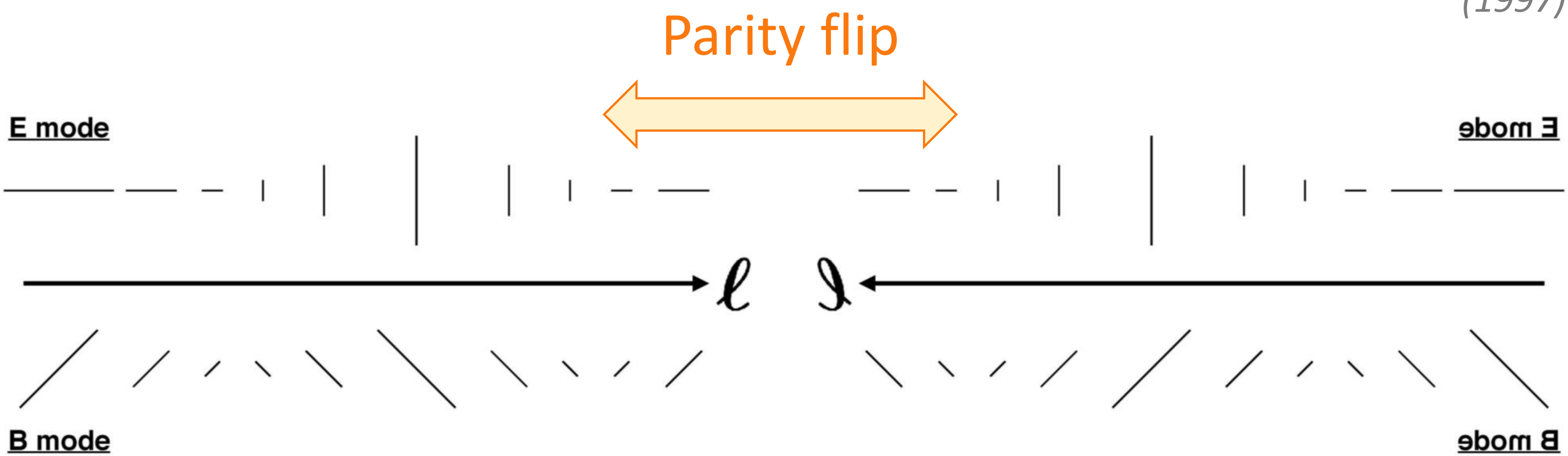
Direction of the Fourier wavenumber vector

- E-mode: Polarisation directions are **parallel or perpendicular** to the wavenumber direction
- B-mode: Polarisation directions are **45 degrees tilted** w.r.t the wavenumber direction

IMPORTANT": These "E- and B-modes" are jargons in the CMB community, and completely unrelated to the electric and magnetic fields of the electromagnetism!!

Parity transformation

Seljak & Zaldarriaga (1997); Kamionkowski, Kosowsky & Stebbins (1997)



- Two-point correlation functions invariant under the parity flip:

auto correlation

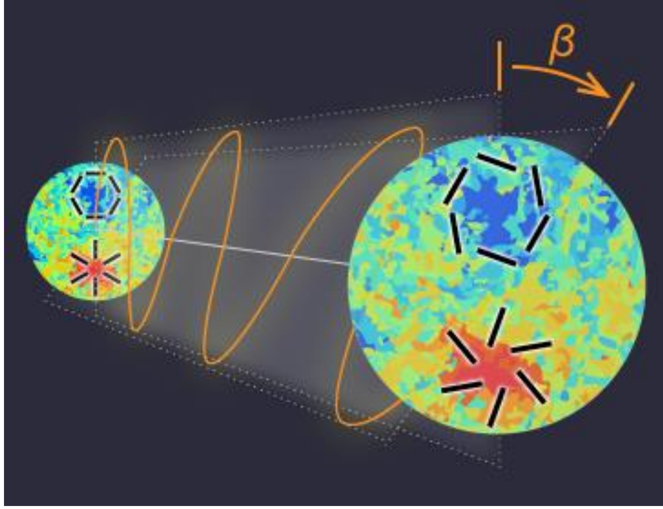
$$\begin{cases} \langle E_\ell E^*_{\ell'} \rangle = (2\pi)^2 \delta^{(2)}(\ell - \ell') C_\ell^{EE} \\ \langle B_\ell B^*_{\ell'} \rangle = (2\pi)^2 \delta^{(2)}(\ell - \ell') C_\ell^{BB} \end{cases}$$

even × even

$$\langle T_\ell E^*_{\ell'} \rangle = \langle E_\ell T^*_{\ell'} \rangle = (2\pi)^2 \delta^{(2)}(\ell - \ell') C_\ell^{TE}$$

- The others, e.g., $\langle T_\ell B^*_{\ell'} \rangle$ and $\langle E_\ell B^*_{\ell'} \rangle$, are not invariant $\cdots (2)$
  - We can use these to probe parity-violating physics!

EB correlation from the cosmic birefringence



Lue, Wang & Kamionkowski (1999); Feng et al. (2005, 2006); Liu, Lee & Ng (2006)

- Cosmic birefringence convert E<-> B as

$$\begin{pmatrix} E_{\ell m} \\ B_{\ell m} \end{pmatrix}^{obs} = \begin{pmatrix} \cos(2\boldsymbol{\beta}) & -\sin(2\boldsymbol{\beta}) \\ \sin(2\boldsymbol{\beta}) & \cos(2\boldsymbol{\beta}) \end{pmatrix} \begin{pmatrix} E_{\ell m} \\ B_{\ell m} \end{pmatrix} \quad \cdots (4)$$

- In power spectra:

$$\langle C_\ell^{EB,obs} \rangle = \frac{1}{2}\left(\langle C_\ell^{EE} \rangle - \langle C_\ell^{BB} \rangle\right)\sin(4\beta) + \langle C_\ell^{EB} \rangle\cos(4\beta) \quad \cdots (3)$$

0

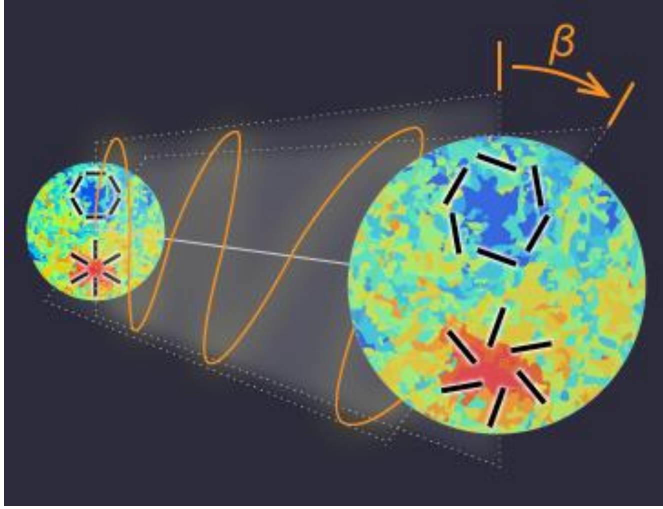
Need to assume a model!

Vanish at the LSS

- Traditionally, one would find β by fitting $C_\ell^{EE,CMB} - C_\ell^{BB,CMB}$ to the observed $C_\ell^{EB,obs}$ using the best-fitting CMB model
  - Assuming the intrinsic $\langle C_\ell^{EB} \rangle = 0$, at the last scattering surface (LSS) (justified in the standard cosmology)

Only with observed data

Zhao et al. 2015;Minami et al. 2019



- Cosmic birefringence convert E<-> B as

$$\begin{pmatrix} E_{\ell m} \\ B_{\ell m} \end{pmatrix}^{obs} = \begin{pmatrix} \cos(2\beta) & -\sin(2\beta) \\ \sin(2\beta) & \cos(2\beta) \end{pmatrix} \begin{pmatrix} E_{\ell m} \\ B_{\ell m} \end{pmatrix} \quad \cdots (4)$$

- We find additional relations

$$\langle C_\ell^{EB,obs} \rangle = \frac{1}{2}\left(\langle C_\ell^{EE}\rangle - \langle C_\ell^{BB}\rangle\right)\sin(4\beta) + \langle C_\ell^{EB}\rangle\cos(4\beta)$$

$$\langle C_\ell^{EE,obs}\rangle - \langle C_\ell^{BB,obs}\rangle = \left(\langle C_\ell^{EE}\rangle - \langle C_\ell^{BB}\rangle\right)\cos(4\beta) - 2\langle C_\ell^{EB}\rangle\sin(4\beta)$$

- $\langle C_\ell^{EE,obs}\rangle = \langle C_\ell^{EE}\rangle\cos^2(2\beta) + \langle C_\ell^{BB}\rangle\sin^2(2\beta) - \langle C_\ell^{EB}\rangle\sin(4\beta)$
- $\langle C_\ell^{BB,obs}\rangle = \langle C_\ell^{EE}\rangle\sin^2(2\beta) + \langle C_\ell^{BB}\rangle\cos^2(2\beta) + \langle C_\ell^{EB}\rangle\sin(4\beta)$

$$\langle C_\ell^{EB,o}\rangle = \frac{1}{2}\left(\langle C_\ell^{EE,o}\rangle - \langle C_\ell^{BB,o}\rangle\right)\tan(4\beta) + \frac{\langle C_\ell^{EB}\rangle}{\cos(4\beta)} \quad \cdots (4)$$

0

No need to assume a model

Vanish at the LSS

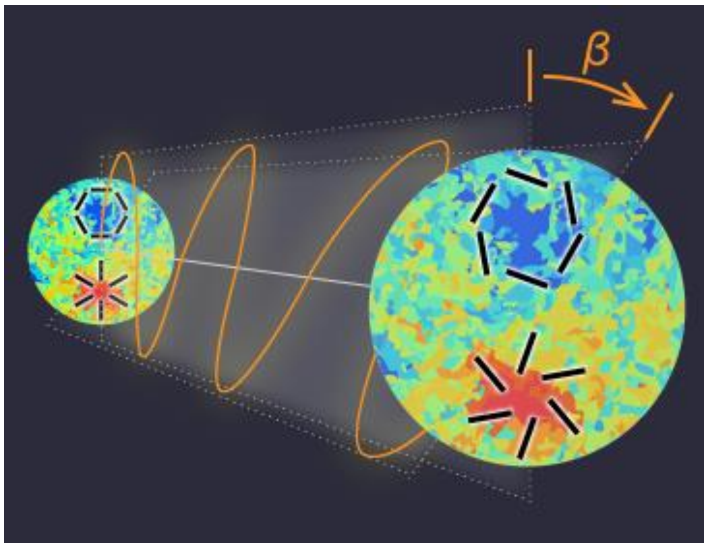
The Biggest Problem: Miscalibration of detectors

Miscalibration of detectors

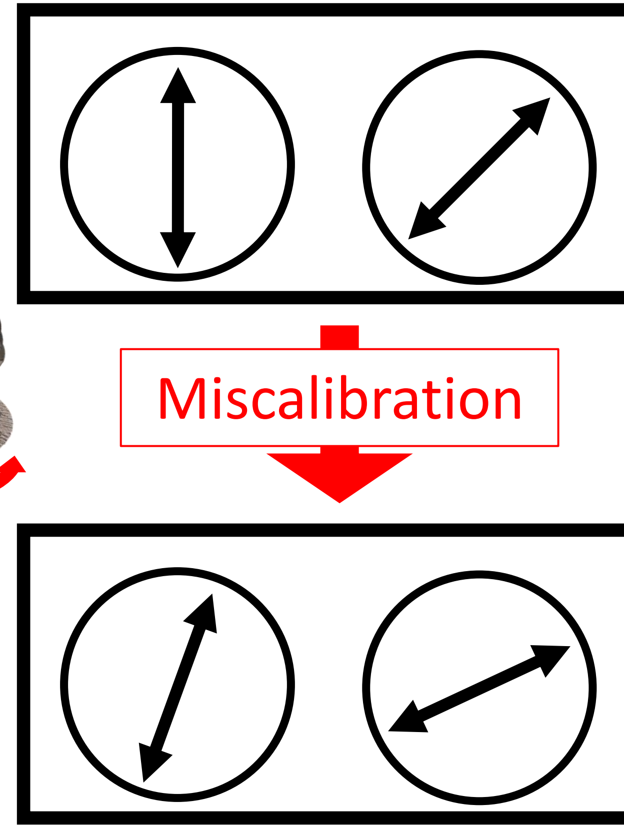
Wu et al. (2009); Komatsu et al. (2011); Keating, Shimon & Yadav (2012)

Cosmic or Instrumental?

Polarisation-sensitive detectors on the focal plane



OR



- Is the polarisation plane rotated by the genuine cosmic birefringence, β ?
- Are the polarisation-sensitive detectors rotated by miscalibration, α, on the sky coordinate (and we did not know)?

rotated by an angle "α" (but we do not know it)

We can only measure the sum, $\alpha + \beta$

The past measurements

Systematic errors on α limited the measurements

Measurement	β + stat. + sys. (deg.)
Feng et al. 2006	$-6.0 \pm 4.0 \pm$ **??**
WMAP Collaboration, Komatsu et al. 2009; 2011	$-1.1 \pm 1.4 \pm \mathbf{1.5}$
QUaD Collaboration, Wu et al. 2009	$-0.55 \pm 0.82 \pm \mathbf{0.5}$
…	…
Planck Collaboration 2016	$0.31 \pm 0.05 \pm \mathbf{0.28}$
POLARBEAR Collaboration 2020	$-0.61 \pm 0.22 +$ **??**
SPT Collaboration, Bianchini et al. 2020	$0.63 \pm 0.04 +$ **??**
ACT Collaboration, Namikawa et al. 2020	$0.12 \pm 0.06 +$ **??**
ACT Collaboration, Choi et al. 2020*	$0.09 \pm 0.09 +$ **??**

First measurement

Uncertainty in the calibration of α has been the major limitation

*used optical model , "as-designed" angles

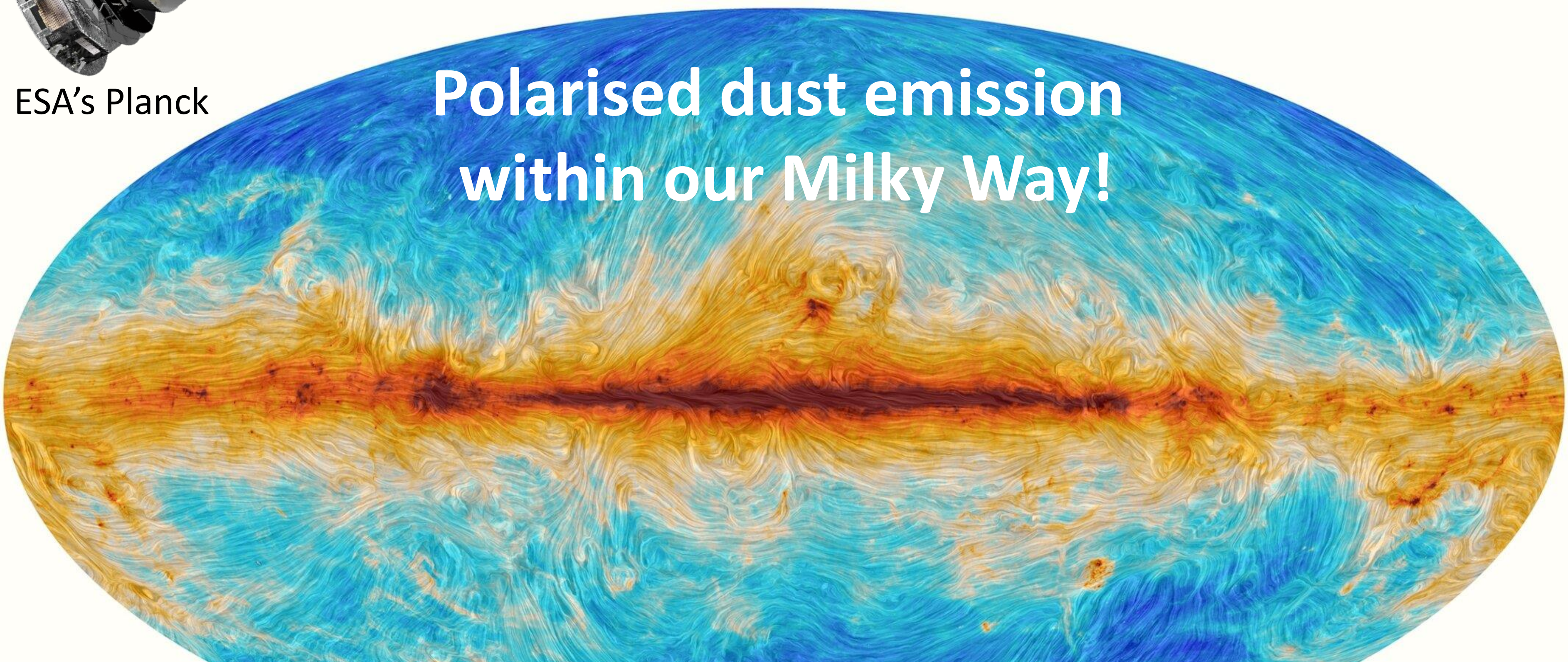
- Other way to calibrate?

Crab nebula, Tau A (Celestial source)	0.27 deg. (Aumont et al.(2018))
Wire grid	1.00 deg. ? (Planck pre launch)

The Key Idea: The polarised Galactic foreground emission as a calibrator

Credit: ESA

ESA's Planck



Polarised dust emission within our Milky Way!

Emitted "right there" - it would not be affected by the cosmic birefringence.

Directions of the magnetic field inferred from polarisation of the thermal dust emission in the Milky Way

Searching for birefringence

Minami et al. (2019)

Idea: Miscalibration of the polarisation angle α rotates both the FG and CMB, but β affects only the CMB

$$E^{\mathrm{o}}_{\ell,m} = E^{\mathrm{fg}}_{\ell,m}\cos(2\alpha) - B^{\mathrm{fg}}_{\ell,m}\sin(2\alpha) + E^{\mathrm{CMB}}_{\ell,m}\cos(2\alpha+2\beta) - B^{\mathrm{CMB}}_{\ell,m}\sin(2\alpha+2\beta) + E^{\mathrm{N}}_{\ell,m}$$

$$B^{\mathrm{o}}_{\ell,m} = E^{\mathrm{fg}}_{\ell,m}\sin(2\alpha) + B^{\mathrm{fg}}_{\ell,m}\cos(2\alpha) + E^{\mathrm{CMB}}_{\ell,m}\sin(2\alpha+2\beta) + B^{\mathrm{CMB}}_{\ell,m}\cos(2\alpha+2\beta) + B^{\mathrm{N}}_{\ell,m}$$

noise

$\cdots (5)$

From them, we derived

$$\langle C_\ell^{EB,\mathrm{o}}\rangle = \frac{\tan(4\alpha)}{2}\left(\langle C_\ell^{EE,\mathrm{o}}\rangle - \langle C_\ell^{BB,\mathrm{o}}\rangle\right) + \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(\langle C_\ell^{EE,\mathrm{CMB}}\rangle - \langle C_\ell^{BB,\mathrm{CMB}}\rangle\right) + \frac{1}{\cos(4\alpha)}\langle C_\ell^{EB,\mathrm{fg}}\rangle + \frac{\cos(4\beta)}{\cos(4\alpha)}\langle C_\ell^{EB,\mathrm{CMB}}\rangle. \quad \cdots (6)$$

Measured

Known accurately

- For the baseline result, we ignore the intrinsic EB correlations of the FG and the CMB
  - The latter is justified but the former is not
  - We will revisit this important issue at the end

Likelihood for determination of α and β

Minami et al. (2019)

Single frequency case, full sky data

$$-2\ln\mathcal{L} = \sum_{\ell=2}^{\ell_{\max}} \frac{\left[C_\ell^{EB,\mathrm{o}} - \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right) - \frac{\sin(4\beta)}{2\cos(4\alpha)}\left(C_\ell^{EE,\mathrm{CMB}} - C_\ell^{BB,\mathrm{CMB}}\right)\right]^2}{\mathrm{Var}\left(C_\ell^{EB,\mathrm{o}} - \frac{\tan(4\alpha)}{2}\left(C_\ell^{EE,\mathrm{o}} - C_\ell^{BB,\mathrm{o}}\right)\right)} \quad \cdots (7)$$

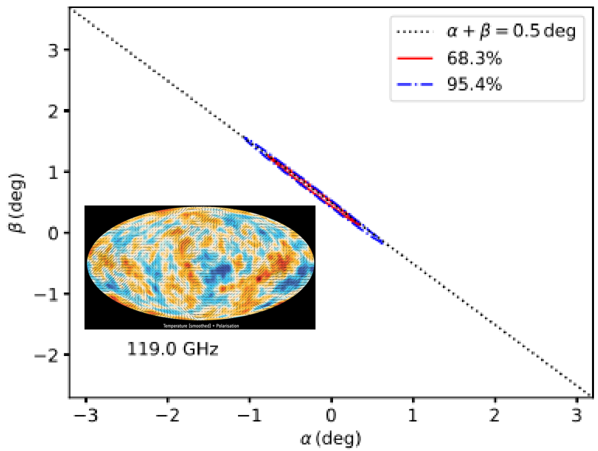
- We determine α and β simultaneously using this likelihood
- For analysing the Planck data, we use the multi-frequency likelihood developed in Minami and Komatsu (2020a)
- We first validate the algorithm using simulated data

How does it work? →

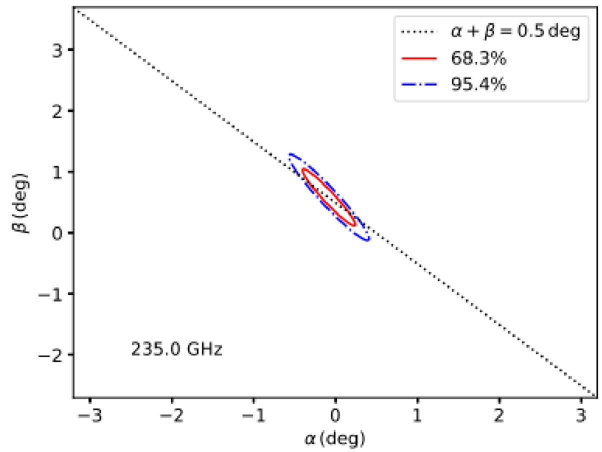
How does it work?

Minami et al. (2019)

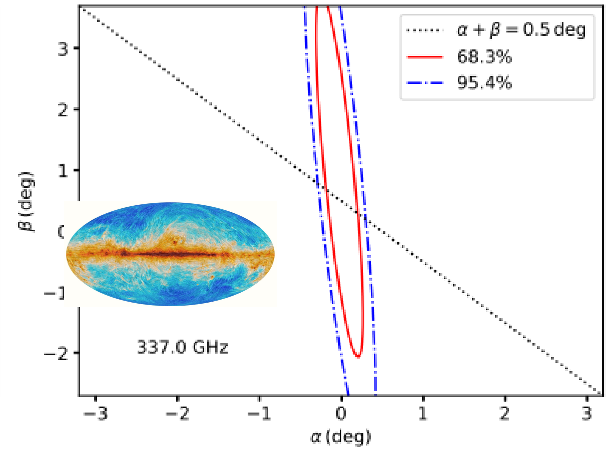
Simulation with future CMB data (LiteBIRD)



CMB channel (119 GHz)



Mid freq. (235 GHz)



Dust FG channel (337 GHz)

- The CMB signal determines the sum of two angles, $\alpha + \beta$
  - Diagonal line
- The FG determines only α
- Mid freq. : breaking the degeneracy with FG signal!
  - $\sigma(\beta) \sim \sigma(\alpha)$, since $\sigma(\alpha + \beta) \ll \sigma(\alpha)$

Application to the Planck Data (PR3, released in 2018)

$\ell_{\mathbf{min}} = \mathbf{51}, \ell_{\mathbf{max}} = \mathbf{1500}$ **(the same values used by Planck team)**

- We used Planck High Frequency Instrument (HFI) data
  - **100, 143, 217, and 353 GHz**

Information for experts

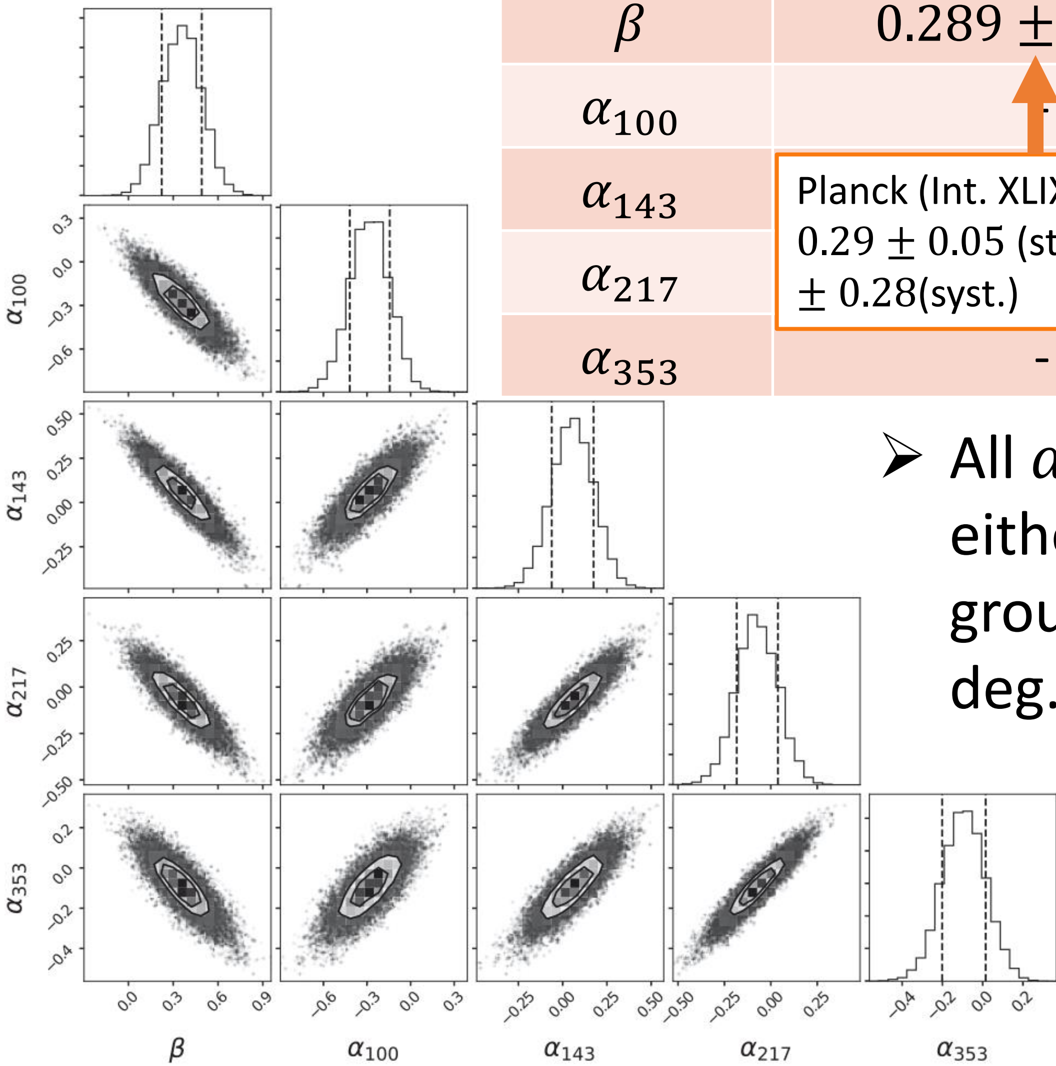
- Power spectra calculated from "Half Missions" (HM1 and HM2 maps)
- Mask (using NaMaster [Alonso et al.]), apodization by "Smooth" with 0.5 deg
  - Bright CO regions. Bright point sources. Bad pixels.
- $I \to P$ leakage due to the beam is corrected using QuickPol [Hivon et al.]
  - It does not change the result even if we ignore this correction: good news!

Minami & Komatsu (2020b)

Main results: $\beta > 0$ at 99.2% (2.4σ)

Angles	$\alpha_\nu = 0$	Results (deg.)
β	0.289 ± 0.048	0.35 ± 0.14
α_{100}	-	-0.28 ± 0.13
α_{143}		0.07 ± 0.12
α_{217}		-0.07 ± 0.11
α_{353}	-	-0.09 ± 0.11

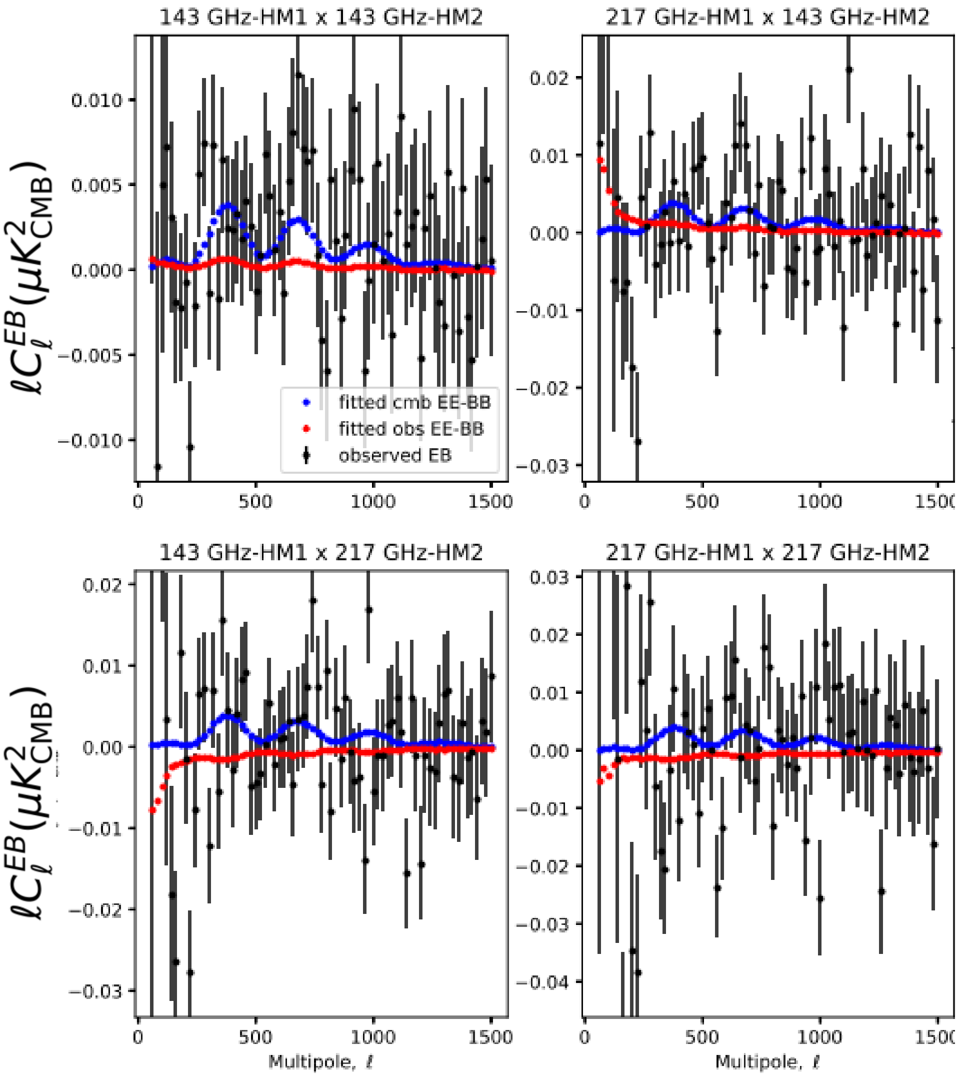
Planck (Int. XLIX):
0.29 ± 0.05 (stat.)
$\pm\, 0.28$(syst.)



- All α_ν are consistent with zero either statistically, or within the ground calibration error of 0.28 deg.
  - Removing α_{100} did not change β
  - $\beta = 0.35$ is consistent with the Planck's result

EB power spectra (Black dots)

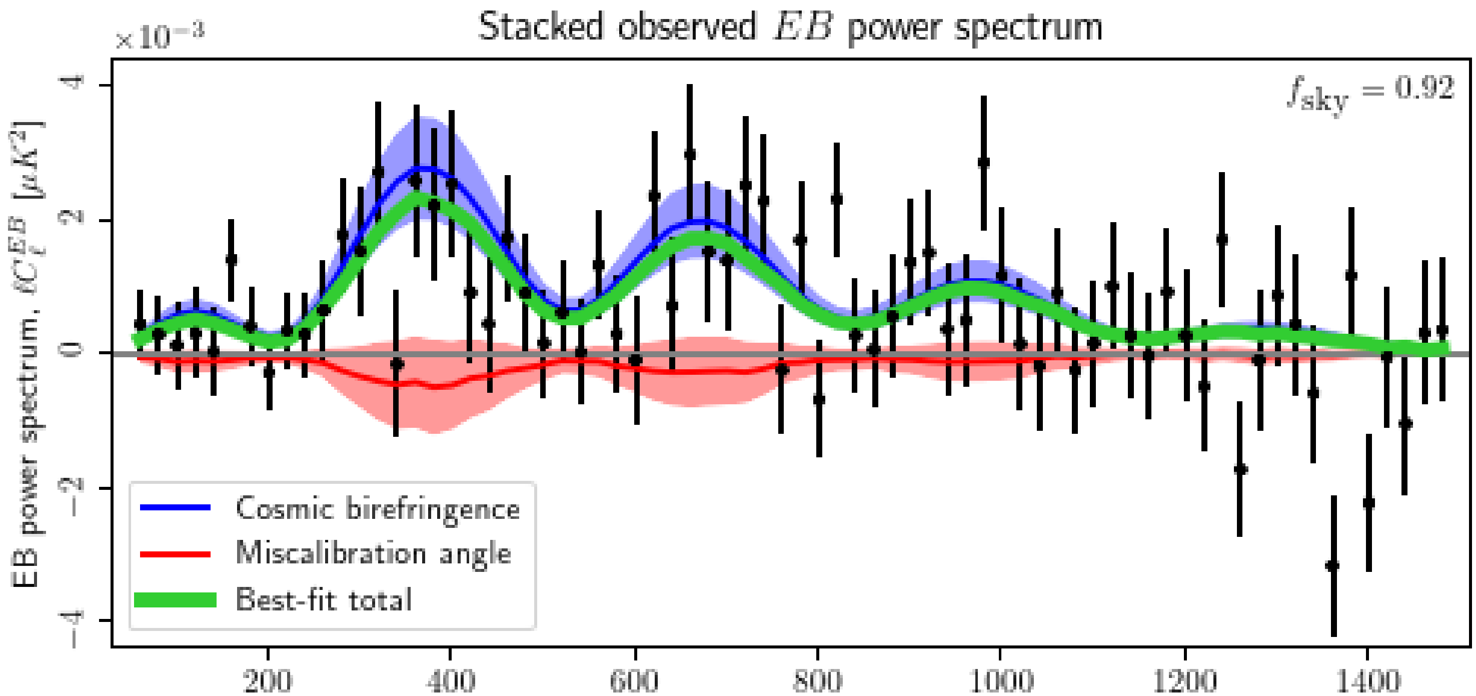
Minami & Komatsu (2020b)



- Can we see $\beta = 0.35 \pm 0.14°$ by eyes?
- Red: The observed signal attributed to the miscalibration angle, α_ν
- Blue: The CMB signal attributed to the cosmic birefringence, β
- Red + Blue is the best-fitting model for explaining the data points (black dots)

Planck HFI+LFI+WMAP

Eskilt & Komatsu (2022)



- Including WMAP data: $\beta = 0.342^{+0.094°}_{-0.091}$
  - Significance increases to 3.6σ

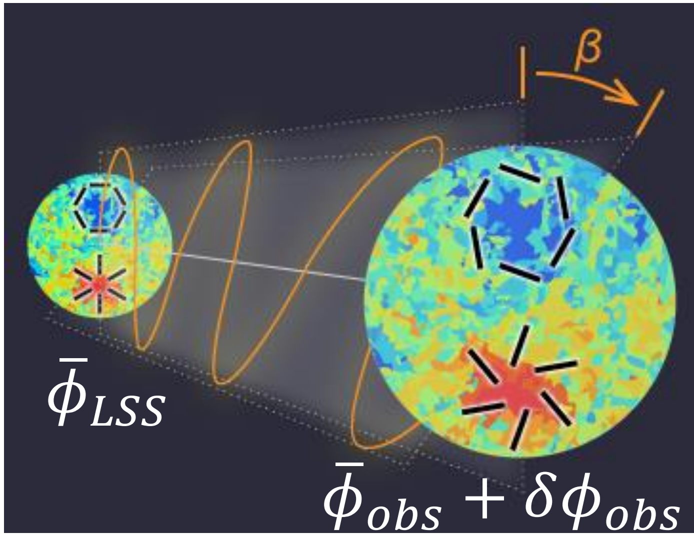
Implications

Minami & Komatsu (2020b)); Diego-Palazuelos, Eskilt, et al. (2022);Eskilt & Komatsu (2022)

What does it mean for your models of dark matter and energy?

- When a Lagrangian density includes a Chern-Simons coupling between a pseudo-scalar field and the electromagnetics tensor as:

$$\mathcal{L} \supset \frac{1}{4} g_{\phi\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} \quad \cdots (9)$$



- The birefringence angle is

$$\beta = \frac{g_{\phi\gamma}}{2} \left(\bar{\phi}_{obs} - \bar{\phi}_{LSS} + \delta\phi_{obs} \right) \quad \cdots (10)$$

Carroll, Field & Jackiw (1990); Harari & Sikivie (1992); Carroll (1998); Fujita, Minami, et al. (2020)

- This measurement yields

$$g_{\phi\gamma} \left(\bar{\phi}_{obs} - \bar{\phi}_{LSS} + \delta\phi_{obs} \right) = (1.2 \pm 0.3) \times 10^{-2} \text{ rad.} \quad \cdots (11)$$

How about the foreground EB?

Minami et al. (2019); Minami (2020);Minami & Komatsu (2020b); Diego-Palazuelos, Eskilt, et al. (2022);Eskilt & Komatsu (2022)

If the intrinsic foreground (FG) *EB* exists, our method interprets it as a miscalibration angle α

- Thus, $\alpha \to \alpha + \gamma$, where γ is the parameter of the intrinsic EB
  - The sign of γ is the same as the sign of the foreground EB
- We thus can determine:

FG: $\alpha + \gamma$

CMB: $\alpha + \beta$

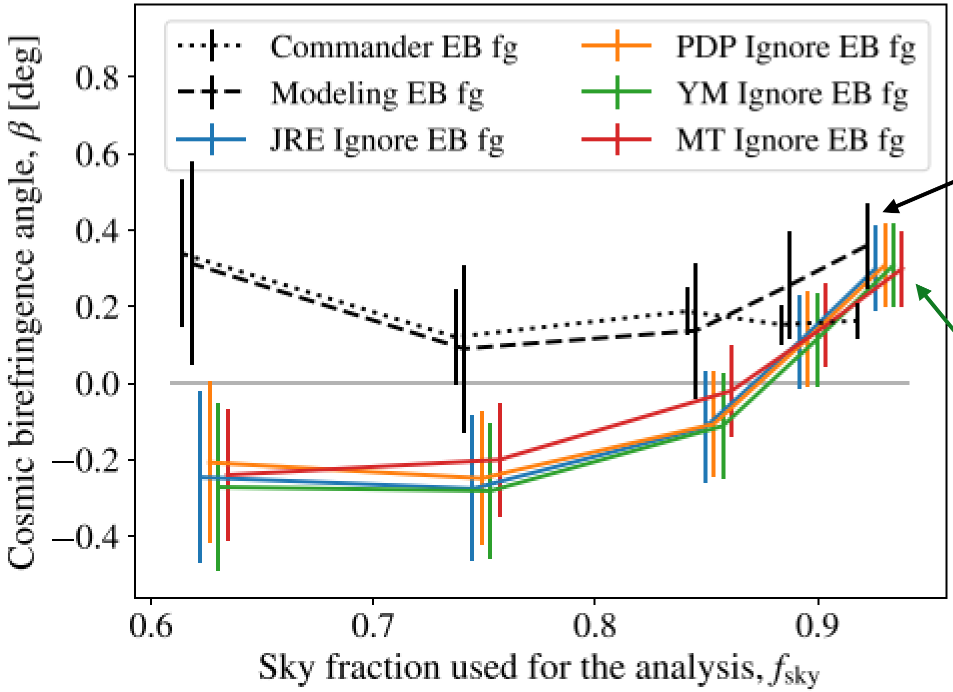
$\Rightarrow$ $\boldsymbol{\beta - \gamma = 0.34 \pm 0.09}$ **deg.**

- There is evidence for the dust-induced $TE_{dust} > 0$ & $TB_{dust} > 0$; then, we'd expect $EB_{dust} > 0$ [Huffenberger et al.], i.e., $\gamma > 0$. If so, β increased further…
  - We can give a lower bound on β

What if the model is taken into account?

Including foreground model: Planck HFI (PR4, released in 2020)

Diego-Palazuelous et al (2022)



With FG model

$\beta = 0.36 \pm 0.11$ deg

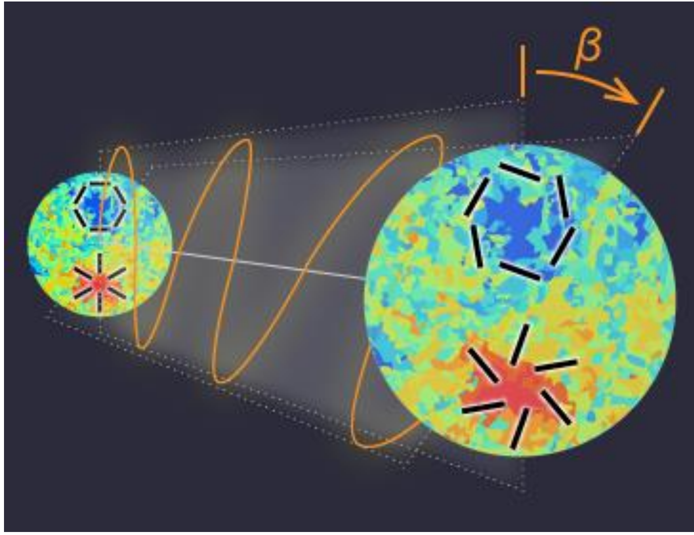
Without FG model

$\beta = 0.30 \pm 0.11$ deg

- Smaller sky fraction decreases $\beta(= \beta - \gamma)$
  - It is known that EB^{dust} becomes for smaller sky fraction
- γ_ℓ is estimated from Planck 353 GHz map

With FG model, β is stable

Conclusion



- We find a hint of the parity violating-physics in the CMB polarisation:

  $\beta = 0.35 \pm 0.14$ deg. (68% C.L.)

- Planck + WMAP

  $\beta = 0.34 \pm 0.09$ deg. (68% C.L.)

*Higher statistical significance is needed to confirm this signal

- New method finally makes impossible to possible:
  - Use foreground signal to calibrate detector rotations
  - Our method can be applied to any of the **existing** and **future** CMB experiments
- We should be possible to test the signal is true or only a coincidence
  - If confirmed, it would have important implications for the dark matter/energy.

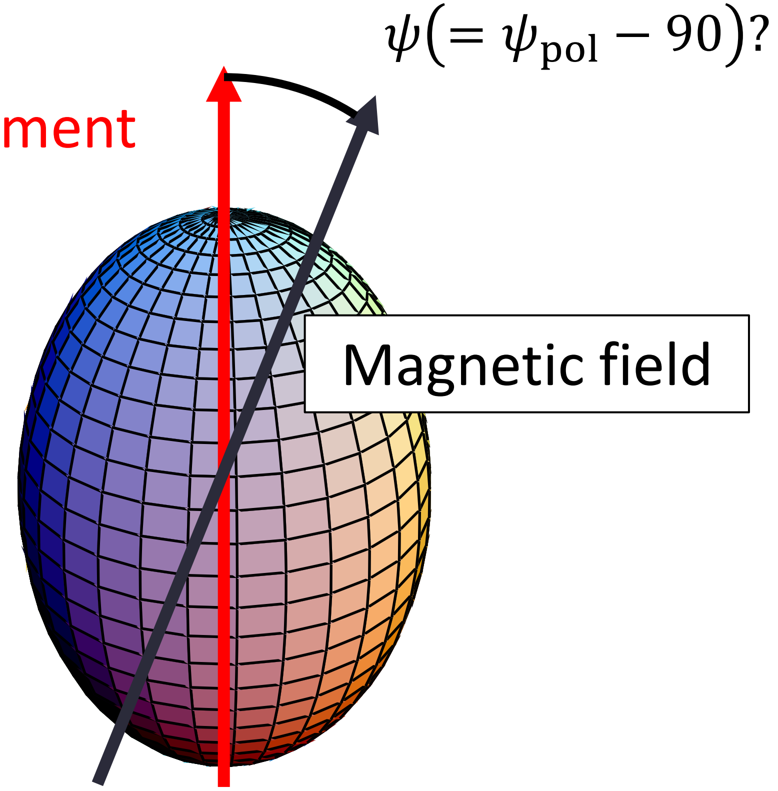
Backups

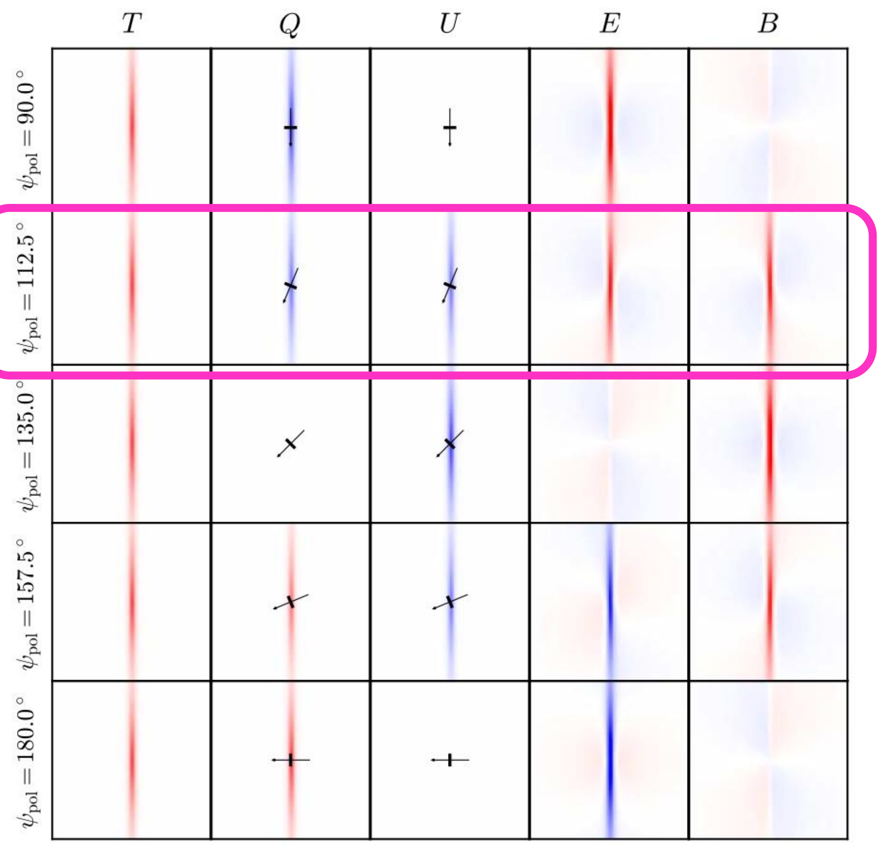
Ideas for discussion

- Are there any good calibration source of microwave?
  - In other bands, protoplanetary disc can be used
- Any good foreground models?
  - Connection with galactic science
- Any systematic uncertainty to create miscalibration angle (like) bias?
  - If any, it becomes an important issue for future CMB missions
- Any other physics which convert E-mode to B-mode except for birefringence?
- Is the earth in special position?
  - The potential of the pseudoscalar particle varies when the earth is in outer edge of the galaxy

Filament model

Huffenberger, Rotti, & Collins (2019)
Clark, Kim, Hill, & Hensley (2021)





- Model of polarised dust emission by spheroidal filamentary structures of hydrogen clouds
- Misalignment between the filament and magnetic field can generate $TE>0, TB>0$, and $EB>0$

Estimating EB from TB

Clark et al. (2021); Diego-Palazuelos, Eskilt, et al. (2022)

- In generic approach, we relate EB to TE as

Unknown
$$\frac{C_\ell^{EB,dust}}{C_\ell^{EE,dust}} \propto \frac{C_\ell^{TB,dust}}{C_\ell^{TE,dust}}$$
Measured

- Our ansatz motivated by the filament model:

$$C_\ell^{EB,dust} = A_\ell C_\ell^{EE,dust} \sin\left(4\psi_\ell^{dust}\right)$$

$A_\ell \ll 1$

$$\psi_\ell^{dust} = \frac{1}{2}\arctan\left(\frac{C_\ell^{TB,dust}}{C_\ell^{TE,dust}}\right)$$

- Then we can put them into a expression of γ as

$$\gamma_\ell \simeq A_\ell \frac{C_\ell^{EE,dust}}{\left(C_\ell^{EE,dust} - C_\ell^{BB,dust}\right)} \frac{C_\ell^{TB,dust}}{C_\ell^{TE,dust}}$$

We can estimate the effect from foreground EB!

In future

With the same method

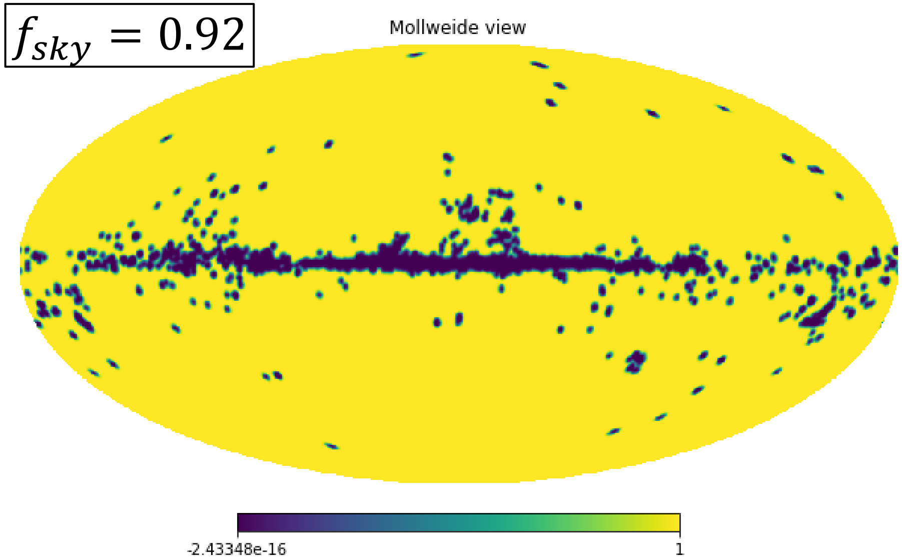
- Application to future satellite mission LiteBIRD (around 2030):
  - Smaller noise level
  - Can push this over 4σ
  - ($\sigma(\beta) \approx 0.1$ deg in Minami&Komatsu (2020a))
- Improvement of our knowledge of the foreground polarization
  - Observation of galaxy
  - More precise foreground modelling

With other calibrators

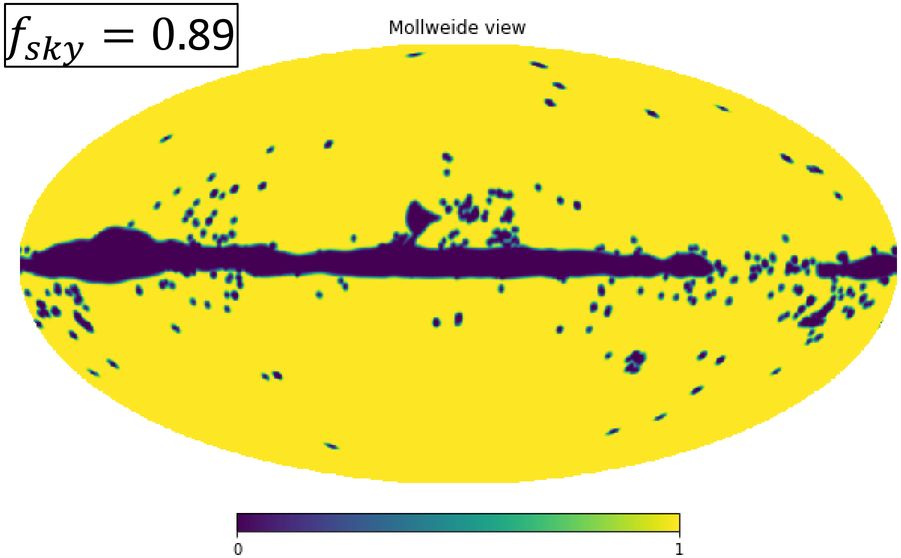
- Improvement of a calibrator on the ground
- Improvement of the Tau A (Crab Nebula) measurement
  - polarised celestial source which Planck also observed

PR4 mask

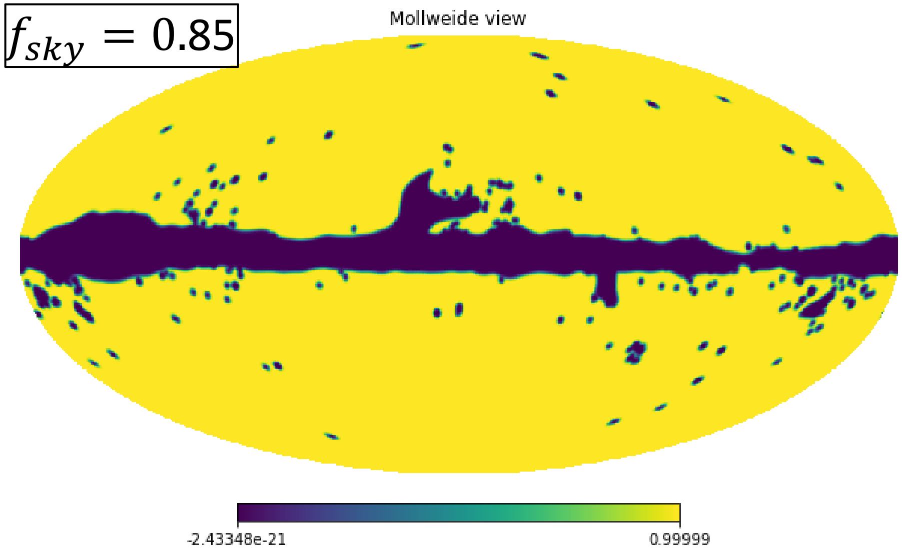
$f_{sky} = 0.92$



$f_{sky} = 0.89$

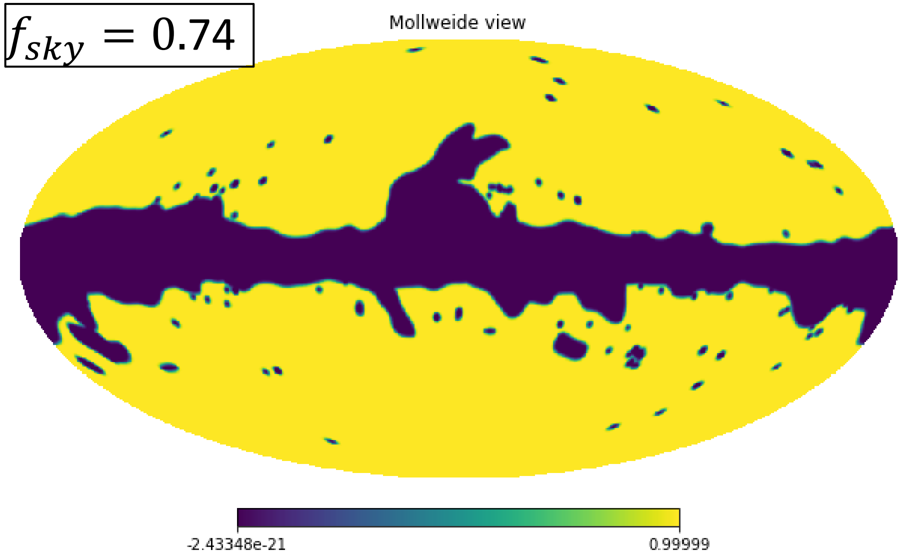


$f_{sky} = 0.85$

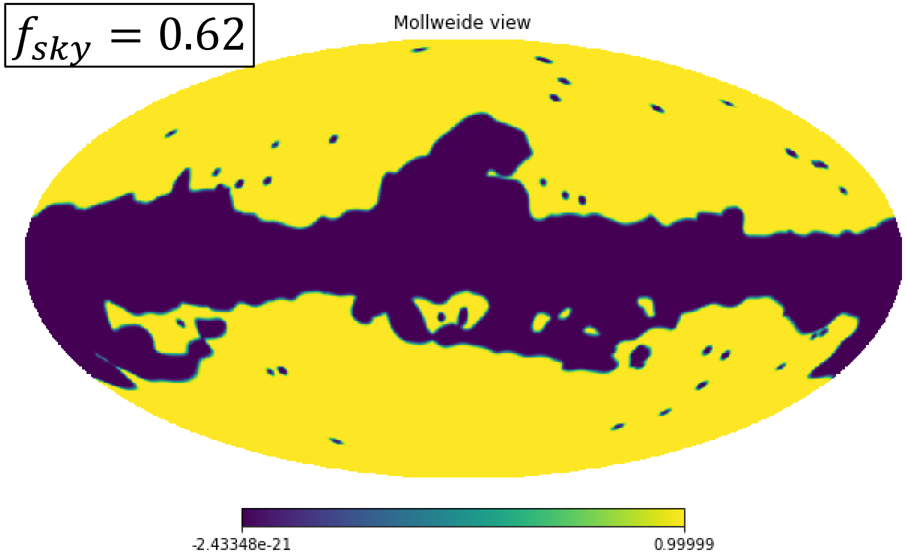


PR4 mask

$f_{sky} = 0.74$



$f_{sky} = 0.62$



PR4 : Frequency dependence

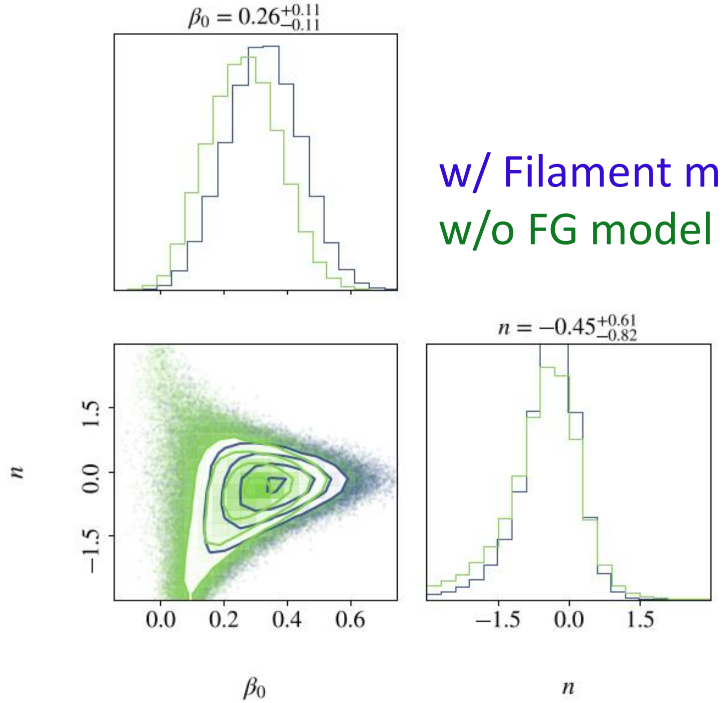
Eskilt (2022)

- Primordial magnetic field create Faraday rotation

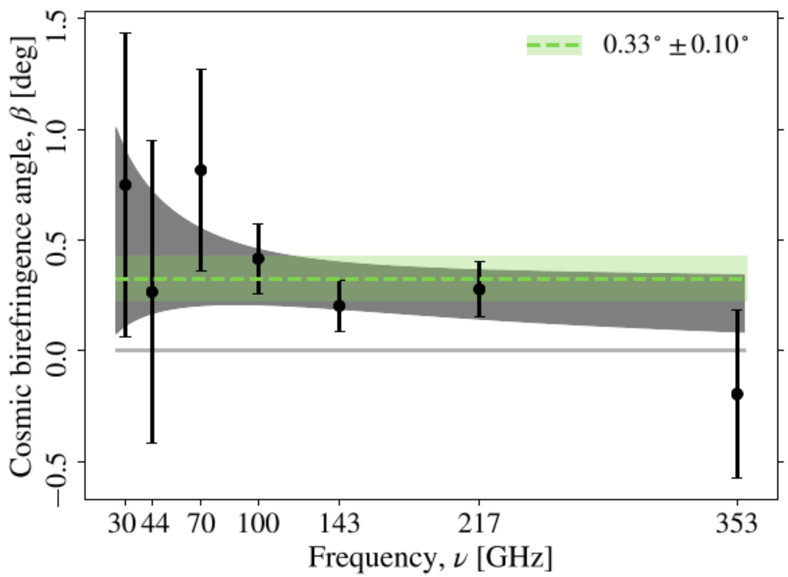
$$\beta_\nu \propto \nu^{-2}$$

- Using Planck HFI (100, 143, 217, 353 GHz) + LFI (30, 44, 70 GHZ)

$$\beta_\nu = \left(\frac{\nu}{\nu_0 (= 150\ \mathrm{GHz})}\right)^n$$

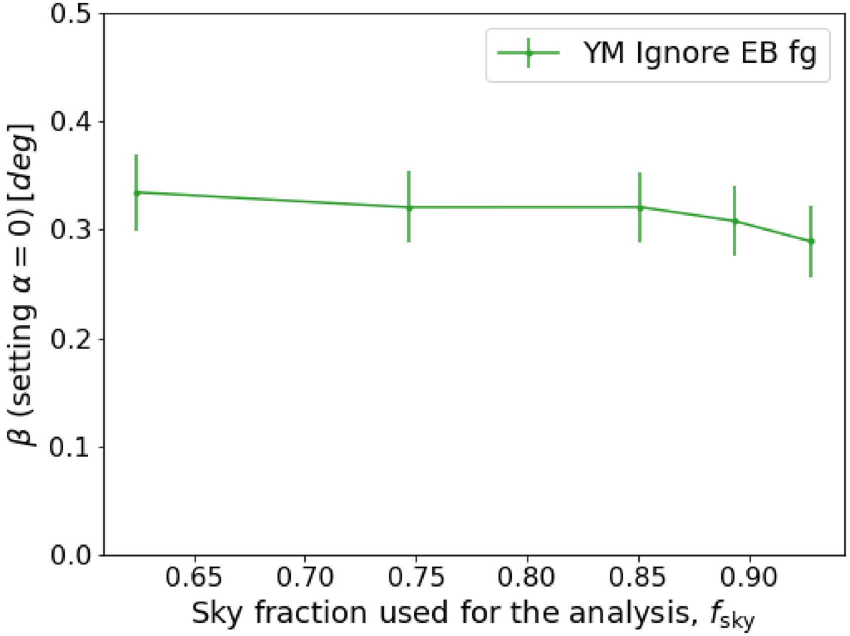


w/ Filament model
w/o FG model



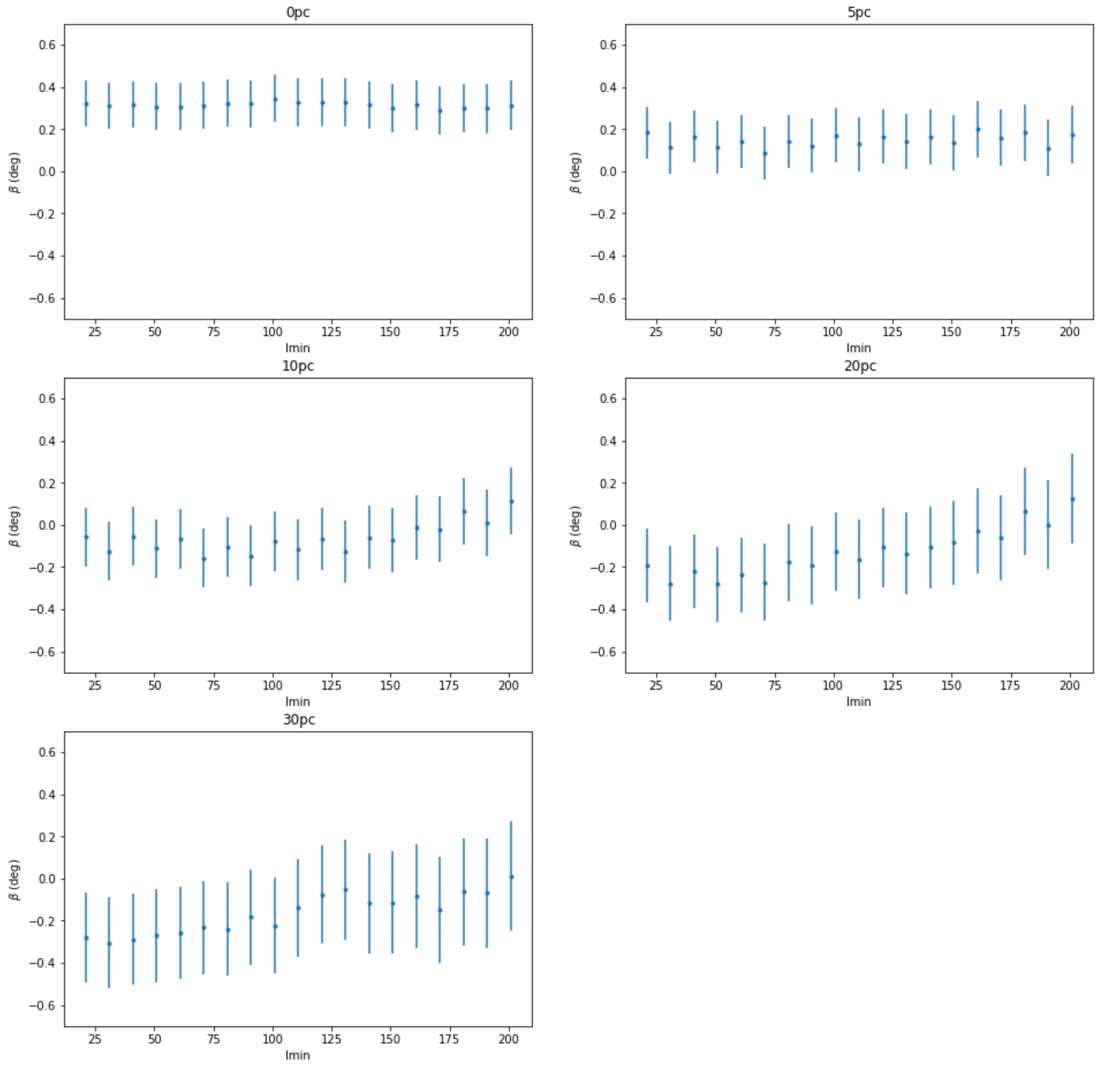
No frequency dependence!

$\alpha + \beta$ against sky fraction



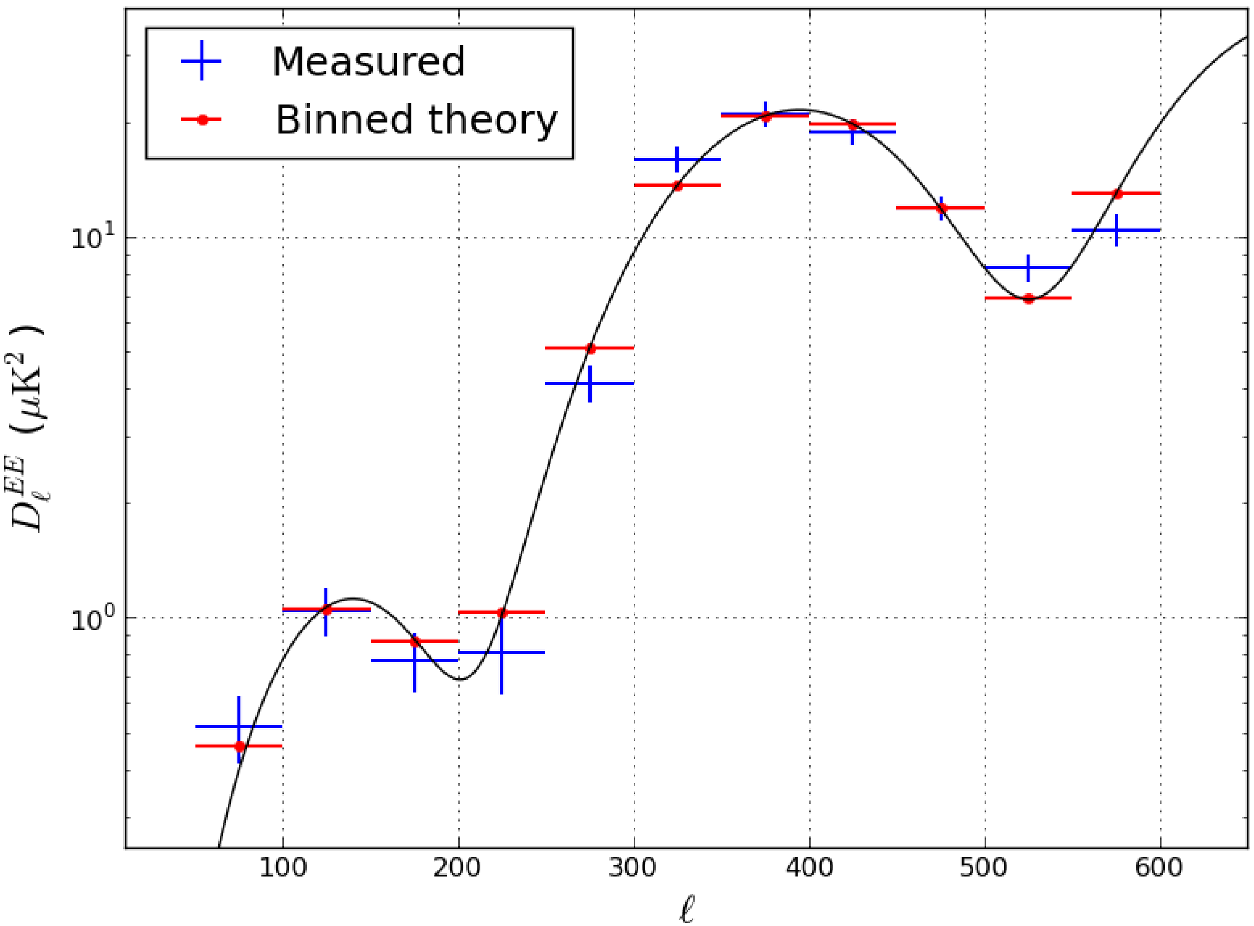
- When we assume $\alpha = 0$ in the estimatin of β, we can estimate $\alpha + \beta$ with the CMB
- $\alpha + \beta$ is stable against the sky fraction
  - Since CMB signal is isotropic in the sky, the reduction of $\beta(= \beta - \gamma)$ is possibly from foreground

ℓ_{min} dependence



POLARBEAR degree scale *E*-mode at 150 GHz

POLARBEAR (2019)

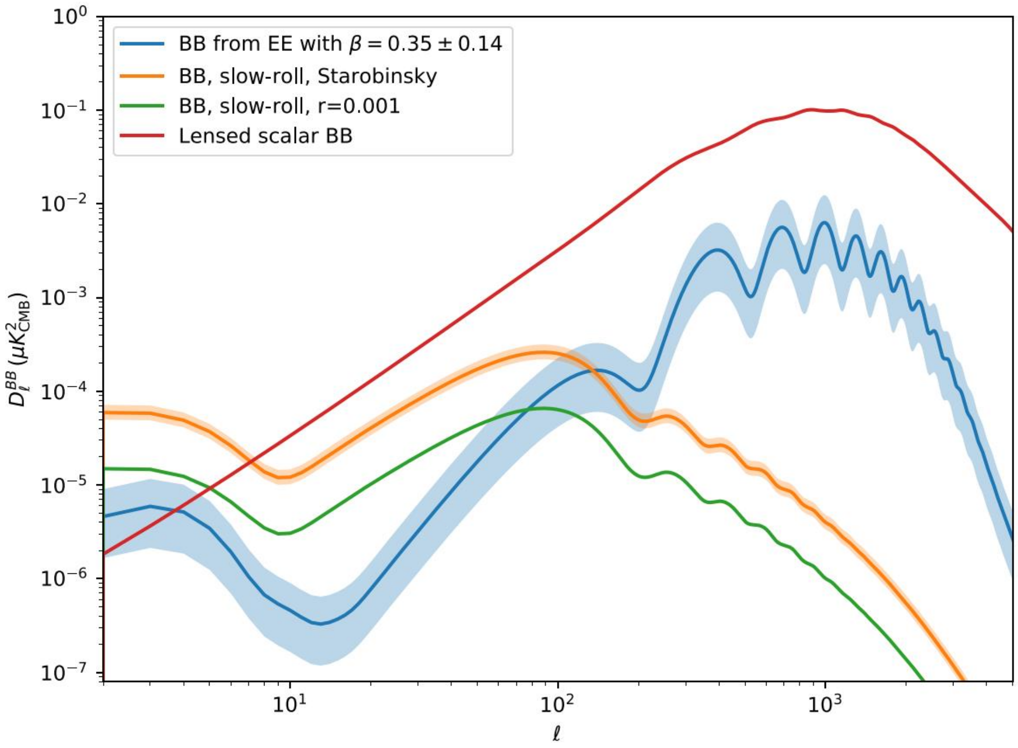


How baound in $\boldsymbol{B}$-mode?

LiteBIRD (2022)

- The effect is small because it is $\propto \beta^2$

$$\langle C_\ell^{BB,obs} \rangle = \langle C_\ell^{EE} \rangle \sin^2(2\beta)$$



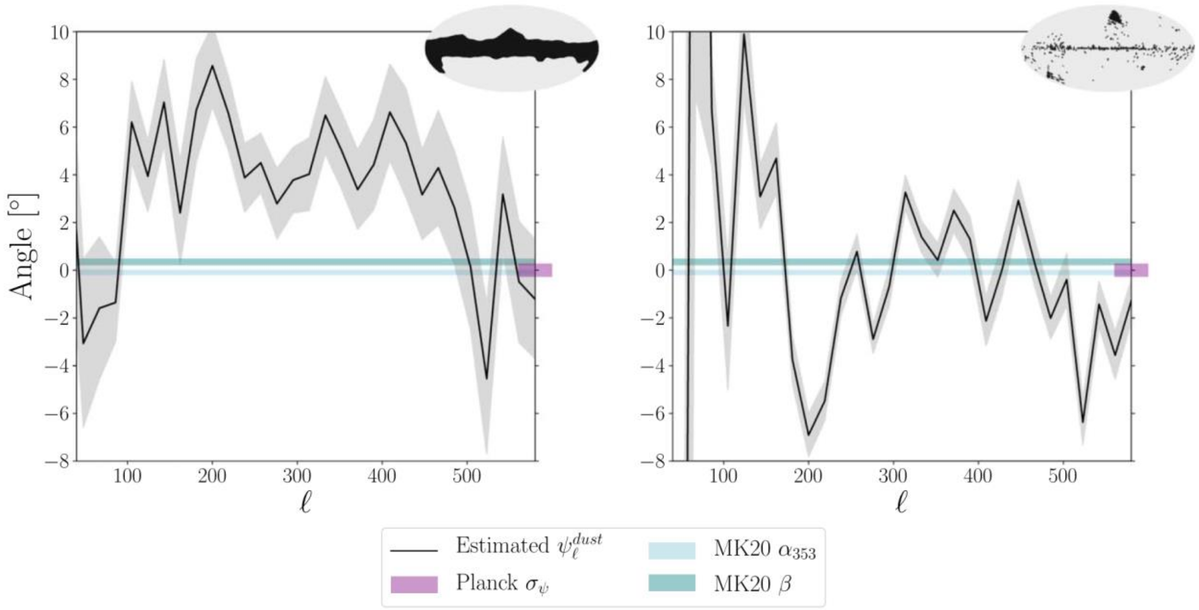
Because B-mode itself is weak,
we need to remove lensing to observe birefringence in B-mode

Foreground EB cross correlation

If FG EB is negative, our assumption does not hold

- Magnetically misaligned filamentary dust structures introduce nonzero EB (Clark, Kim, Hill, & Hensley 2021)

If we select some part of sky area, EB can be small



ℓ dependence of ψ which is proportional to EB